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Evaluating Science Return in Space Exploration Initiative Architectures

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Introduction

On July 20, 1989, President Bush called for a program to return to the Moon and conduct an expedition to Mars, an effort subsequently named the Space Exploration Initiative (SEI). While we recognize that the SEI is not specifically a scientific program, science will be an integral part of the Initiative as the quest for knowledge which drives humans beyond low earth orbit. How we develop and maximize the effectiveness of the SEI science program is a continuing challenge for mission planners. In this paper we define some parameters that might be used to evaluate the science return in SEI mission architectures. Our goal is to maximize the mix of disciplines and the quality of science return as we plan for and embark on the human exploration of the Moon and Mars.

The Problem

Prior to the launching of the maiden voyage for SEI, many mission scenarios or "architectures" will have been considered, discarded, and reworked before the optimum mission plan is selected. The architectures will be chosen on the basis of a variety of factors, including cost, safety, schedule, feasibility, and the overall ability to accomplish mission objectives. From our perspective, an important criterion in architecture selection is how well it enables us to execute a program addressing science objectives. How we go about making these choices during the mission planning phase may mean the difference between an exciting program, rich with scientific advancement, intrigue, and surprising new discoveries, or a disappointingly lackluster program of little value to the science community.

Different architectures create different opportunities for accomplishing science objectives, and certain architectures will be better than others in addressing science questions. How do we evaluate the potential science return of a given architecture? Put another way, given two SEI mission architectures that are for all other purposes equivalent (e.g., based on engineering, fiscal, or managerial constraints), how do we determine which one enables a greater or better science return?

To attempt to measure the return of science in a given architecture is to try to measure something that is not measurable. No given metrics or units exist that can evaluate adequately the science accomplished in a mission. This is in contrast to most engineering requirements whose evaluation is straightforward and easily quantified. Mission science objectives are more

broadly defined and determining the degree to which they are accomplished is subjective. Part of the reason for this is that the SEI science program is a composite of several disciplines. Furthermore, science performed during lunar and Mars missions will consist of observational, experimental, and theoretical elements. The collective return or value of the science program defies simple appraisal.

We propose a way to visualize the science program and its potential return, defining what a given architecture offers a particular parameter that measures science return. We hope to use this visualization to better understand which mission elements drive the science program as a whole. Of equal importance is how these parameters affect science return for the specific disciplines. Our aspiration is that during final mission planning, these parameters can be configured in the best possible way to prepare us for a varied and fruitful science mission.

Before discussing how we evaluate science, it is helpful to first recognize the top level science objectives and to understand the terminology we use in describing a mission science program.

Science Objectives of the Space Exploration Initiative

The Space Exploration Initiative enables unique scientific investigations on the Moon and Mars. A diverse community of scientists are devising sets of questions that must be answered to better understand the universe and our place in it. These questions define the science objectives that are independent of mission architecture.

Five major science questions or themes were developed for the initial study of SEI mission options (NASA, 1989):

- How were the Earth and Moon formed and what was their early history?
- Did life ever start on Mars?
- What is the relationship between the Sun, planetary atmospheres, and climate?
- Are there worlds around other stars?
- What is the fate of the Universe?

These five questions represent high level themes encompassing many other science goals which include understanding the origin of the Earth-Moon system, geological evolution of the Moon and planets, the nature and evolution of stellar bodies, the existence of planets around other stars, the nature of interplanetary particle physics and fields, and the history of water and climate on Mars (see for example, Nash et al., 1989; Smith, 1990; Mars Science Working Group, 1991; Lunar Exploration Science Working Group,

1992). In addition, there are many other issues in applied science, such as human health and performance in space and materials sciences, that will be advanced by SEI.

Opportunities, Requirements, and Implementation

Science questions such as those listed above are pursued regardless of the program or mission. This is in contrast to science opportunities, which can be broken into two categories: (1) specific opportunities that are provided by mission capabilities defined in a SEI architecture, and (2) general opportunities resulting from the properties of the body being studied (e.g., use the Moon as an airless, stable, slowly rotating, low gravity platform for observing the universe.) Science requirements dictate how we go about answering a question or addressing the problem, i.e., what data do we need to take, what observations must we make? The final step is *implementation*, or how the requirement is satisfied using a particular experimental process or instrument. Examples of science implementation might be designating pathways for geologic traverses, or determining a specific instrument design to conduct an experiment or make an observation.

Scientists are currently defining research objectives for astrophysics, geoscience, space physics, biological science, and materials science associated with lunar and planetary bases (e.g., Morrison, 1990). Requirements for each of these disciplines are also being prepared and will vary depending on the discipline and the nature of the observations or experiments. Lunar geologists want to explore and sample specific features on and below the surface; interesting sites are scattered randomly about the Moon, and include the poles and the far side. Astronomers want to place observatories on any flat surface at latitudes that provide for the best view of the entire sky and, for radio astronomy, the least noise interference from the Earth. Space physicists want to emplace sensitive detectors, oriented optimally to measure particle density and flux, far from man-made nuclear sources that might be resident at a lunar outpost.

The various science disciplines may share some common requirements, but such requirements are not always compatible, particularly when considering where to locate a landing site on the Moon or how long to remain at any given site.

Measuring Science Efficacy

We acknowledge that SEI science objectives are broadly defined and the requirements for "good" science are subjective and difficult to quantify. Therefore to evaluate mission architectures for the degree to which they accommodate a multidisciplinary science program, requires a novel approach. We do not see any way to quantify the science return with a unit measurement. Instead we suggest a method for visualizing the science return in terms of parameters which "frame" the science potential. These parameters can be used to describe the amount and quality of science performed for the entire mission program. We will see that considering the science program as a whole is not as effective as looking at it in terms of specific disciplines and the parameters which drive each discipline.

The Parameters of Time, Capability, and Access

The degree to which mission science is accomplished can be characterized by three parameters: time, access, and capability (Synthesis Group, 1991). Time includes the days on the surface of the Moon or Mars, and the number and duration of extra-vehicular activities for the mission. It may also include the number of separate mission visits or sorties to a given site of designated scientific interest. Access is the means to reach selected sites or areas of a given planet and includes the numbers of sites visited (by human or robots), frequency of visits, vehicles for transport or delivery of crew or hardware, and the mode of travel over a planetary surface. As an example of the latter consideration, a crew could "hop" to a distant site ballistically, enabling investigation of a point on the planet, or the crew could conduct long-range surface traverses. Both modes of travel permit the exploration of parts of the planet that would otherwise be unvisited; the former allows detailed investigation at a single site, whereas the latter permits the intervening terrain to be reconnoitered during transit. The two modes of travel give different levels of scientific return.

Capability is a broader category, somewhat more difficult to quantify. It encompasses the mass and quality of scientific instrumentation delivered to the surface, the number of experiments, the local mobility available for crew and equipment, and the number of crew members to perform science duties, including their cumulative skills for executing experiments and performing observations. Capability also embraces the means for sampling the lunar or martian surface and

subsurface by digging, trenching, or coring and includes the amount and quality of observations that can be made enroute to a site, which we refer to as traverse science. An example of traverse science would be the collection of certain geophysical data while roving between study sites. Finally, capability involves the amount and sophistication of infrastructure support at an outpost or site; such support includes power, data links and storage, laboratory space and instrumentation, and crew.

If we think of the science return in general, and within these three framing parameters of time, access, and capability, we can envision a three-dimensional plot that defines a mission envelope for science (figure 1). This plot represents a space within which the scientific return of a given mission architecture can be measured. In general, the larger the area of the triangle defined by the three point plot on the axes, the greater or better the science return. This envelope or threshold allows us to make decisions regarding the science content and implementation for subsequent phases within the long-term SEI mission plan.

Mission Phases and Science Return

As we consider the value of science in a given architecture, it is vital to recognize the point in the mission at which we are evaluating science. Missions are commonly partitioned into phases, and science is

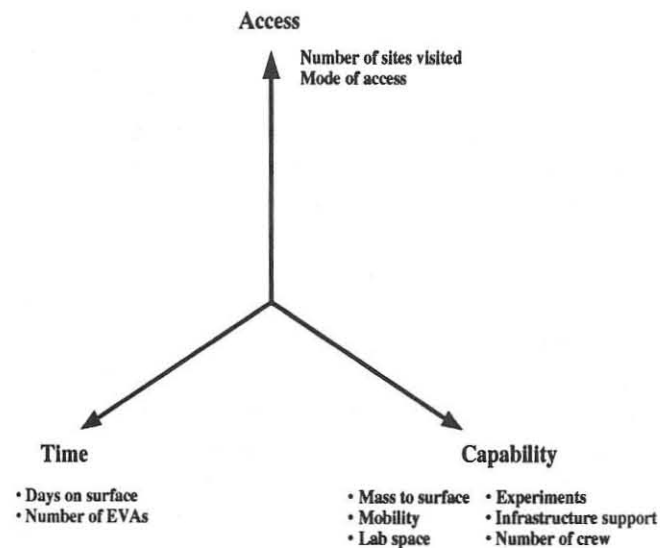


Figure 1. Three-axis plot of time, capability, and access, which define the total scientific return of an implementation of a given architecture.

accomplished to different degrees during certain phases. For an architecture that progressively builds up supporting infrastructure, the collective science return may be very minimal in early phases, but robust during later phases when the mission can support a dedicated, aggressive multi-disciplinary science program.

Different science disciplines may be favored during different phases of a mission. Consider an architecture that first conducts a phase of expeditions at several different sites and later builds a permanent outpost. Expeditions provide minimal infrastructure, but maximize access. An outpost phase can provide greater infrastructure support, but access may be limited to the outpost and local traverses. The science return for geosciences may be high during the expedition phase, but much lower once exploration is restricted to the outpost. In the same architecture, astronomy may be neglected during the expedition phase, but could then see an explosion of data returned once the outpost phase starts and large observatories which require high mass delivery and have a high consumption of electrical power can be supported.

Different Science Disciplines/Different Parameters

The approach to evaluating total science return in terms of access, time and capability is clumsy because it lumps all disciplines together. In fact, specific disciplines are leveraged to different degrees by the various framing parameters. It is helpful to call out the disciplines separately, and characterize each one using those parameters which most affect the potential to successfully accomplish science objectives. We do this for the individual disciplines of geosciences, astronomy and astrophysics, and the laboratory sciences listed in figure 2, plotting each discipline on a three-axis graph of access, time, and capability.

Geoscience

The scientific exploration of the Moon and Mars as planetary objects is an important part of the SEI program. These bodies tell us about planetary processes and history, and reveal the subtleties of the formation of terrestrial planets and the Solar System. Both the Moon and Mars have complicated histories, and a variety of processes have operated at different rates, in different places, and at various times. Such complexity results in heterogeneous and complicated crusts, surfaces which must be visited at a variety of globally distributed sites if we are to fully comprehend their geological records.

Geological exploration can be divided into two categories: reconnaissance and field study (Spudis and Taylor, 1988; Spudis, 1992). The goals of reconnaissance are to acquire an overview of composition, regional setting, surface structural features, and processes. Reconnaissance requires short-term sorties into an area, taking representative samples of large units of regional significance. Some geologists have suggested that reconnaissance on the Moon and Mars would be well-suited to telerobotic exploration (Spudis and Taylor, 1988).

The more ambitious goals of field study are to fully understand the geologic setting, subsurface structure, past environments, processes, and history of an area or region. Field study requires careful, repeated observations and sampling in the field, the mental building of a conceptual model, hypothesis formulation and testing, and revisits to the same locale. Complicated field sites on Earth have been studied for many decades and are still studied fruitfully today by new generations with fresh insights.

The parameters most affecting return for geoscience are access, time on the surface, and the mobility systems available to deliver a crew to a study site. This can be visualized by plotting geosciences on our three-axis plot (figure 2a). Return increases greatly with the number of sites visited because more planetary environments can be characterized, a wider variety of geological processes can be studied, and the potential for unexpected discovery is much greater. More frequent and longer excursions to study geologic features allows for real-time assimilation of data and observations, or more simply, time to think. Longer mission duration allows for on-site sample analysis. Analyzing rocks in real time allows the crew the option of rethinking subsequent excursions, targeting new sites, or returning to sites previously studied. The most important secondary parameter of capability in geoscience is mobility because it enhances access. Mass delivered to the surface is of lesser importance; geologic field work is not equipment intensive; and field tools, because they are carried by the explorer or ferried on a rover, are lightweight and fairly compact.

Astronomy and Astrophysics

The Moon is an ideal platform from which to observe the universe. Its high vacuum, low gravity, seismic stability, and low noise background at radio wavelengths on the far side make it a unique resource for astrophysical and space physics observations. Astronomical observatories would permit high

resolution views into our galaxy and other galaxies, could search for planets around other stars, and could continuously monitor our own home planet. Sensors and collectors could observe the entire spectrum of wavelengths, from DC to gamma ray. Exotic particles and plasmas impinge directly upon the surface of the Moon, permitting its use as a collector for cosmic particles.

Astronomers have attempted to identify optimal locations on the Moon's surface for observatories (Morrison, 1990). Sites on the lunar equator offer continuous views of the entire sky, but polar sites may be preferable for some observations and viewing techniques. For radio astronomy, the lunar far side, permanently shielded from the radio din of the Earth, remains a highly desirable location.

The most important consideration for astrophysics and space physics is the infrastructure support that enables the delivery, assembly, construction (if necessary), operation, maintenance, and data return from surface observatories/stations (figure 2b). Telescopes and space physics instruments are for the most part heavy, require built-in power and data systems, and may entail construction, either of the observatory or the pad upon which it sits. As each of the related infrastructure components improves, so does the capability to support more robust observatories and the quality of the astronomical data.

Instrument mass delivered to the surface is not in itself a good measure of science return because it does not insure that good science is accomplished. For example, a large, heavy telescope might provide only a few specialized observations. On the other hand, geologic equipment weighs very little, but when used by a trained explorer accomplishes much. For this reason, a large mass number for astronomy and a low mass number for geosciences may actually provide science return that is equivalent.

Laboratory Sciences

For laboratory sciences, the quality of experiments is linked to the pressurized space dedicated to host experiments and instruments. More space in the laboratory means that more instrumentation can be accommodated, permitting a greater variety of more complex procedures. Lab experiments might include rock and soil sample examination and analysis, the evaluation of planetary materials for resource extraction, experimental biomedical tests, plant and animal experiments, and agriculture. Secondary factors providing high leverage are enough trained

Geoscience

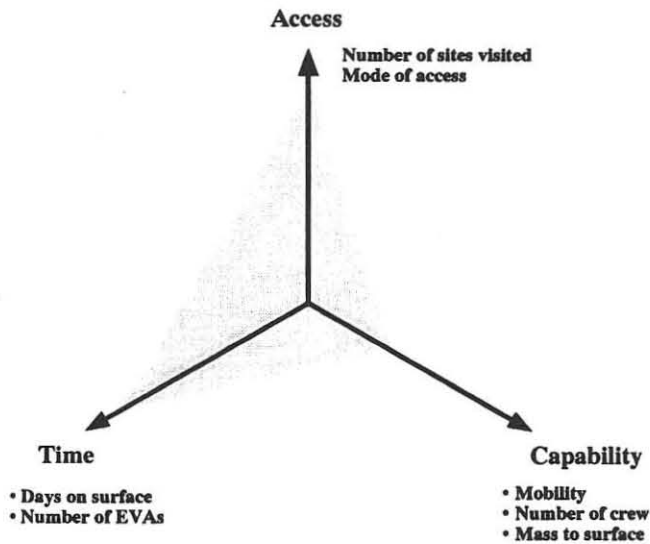


Figure 2a

Astronomy/Astrophysics

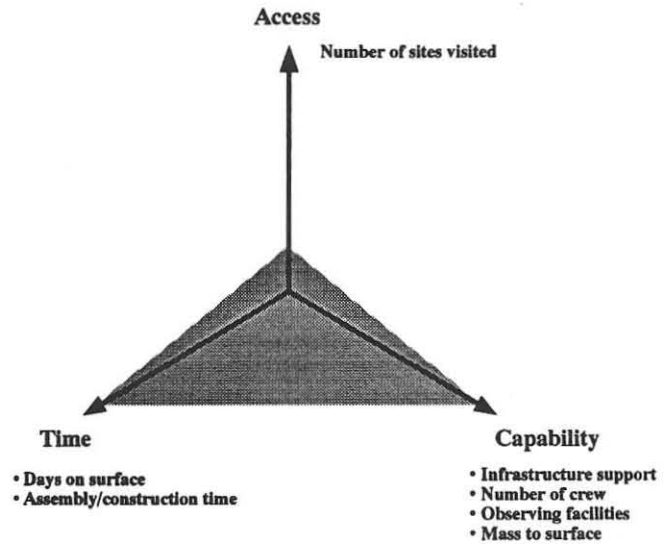


Figure 2b

Laboratory Science

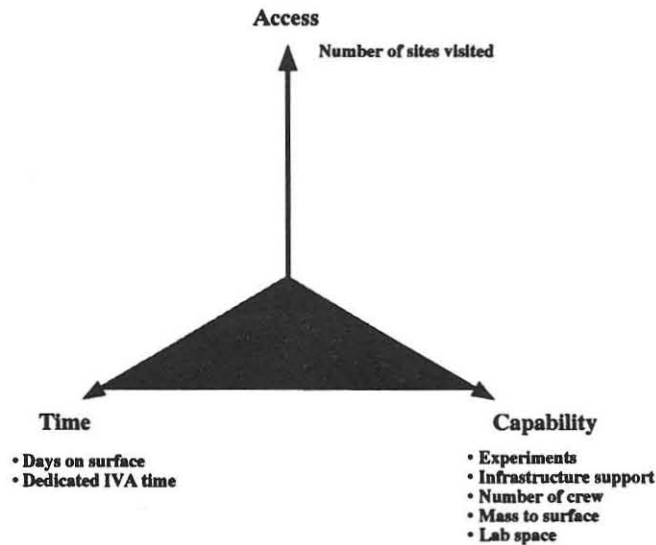


Figure 2c

Figure 2. Three-axis plots for each scientific discipline, showing different return envelopes for each:

- (a) Geoscience, dominated mostly by access and time; the capability is largely determined by local mobility.
- (b) Astronomy and astrophysics, dominated primarily by time and capability; access is of much lesser importance.
- (c) Laboratory science, dominated mostly by capability and time. Because lab science is done at the outpost, it usually has no access requirements, thus producing a two-dimensional surface on this plot.

crew members to conduct the experiments, and enough time in which to perform them (figure 2c). On the other hand, some simple experiments may require longer running times rather than complex analytical facilities.

Because most laboratory experiments would be performed within a pressurized habitat or laboratory enclosure, lab science would be site-independent. Accordingly, access is the least important parameter for leveraging laboratory science. However, sample analysis will be of limited value if there is no ready access to interesting materials.

Thresholds of Science Return

For a given discipline, the science return increases with an increase in the most critical framing parameters. But more than that, as the parameters increase, science return passes through thresholds or step functions in the level of knowledge returned (figure 3). For example, the return for geosciences is enhanced significantly when the mobility changes from sorties on foot to expeditions using a rover. As another example, astrophysics depends heavily upon

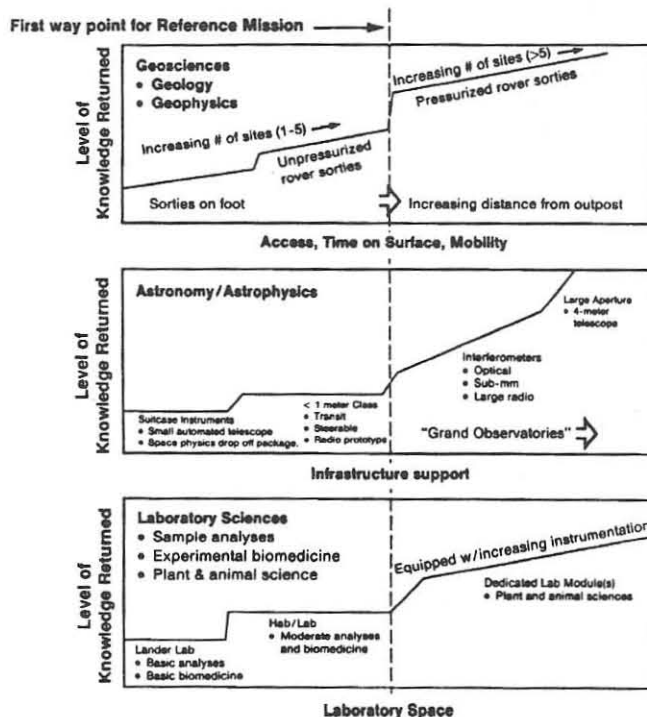


Figure 3. Different disciplines are leveraged to differing degrees by the three variables. In this plot, we see that there are threshold, or step functions for each discipline. The horizontal axis on each graph shows which factors most affect the scientific return by discipline.

telescope infrastructure for its observations. This discipline sees a marked increase in science return as the available capability to deliver and support telescopes increases from hand-carried "suitcase" instruments to telescopes with meter-sized optics. Another major increase in return occurs when several telescopes are combined in an array to form an interferometer.

Evaluating Architectures

To evaluate an architecture for science efficacy, we need to consider it in light of the accomplishments of the different disciplines, collectively in terms of its total science quality and individually in terms of specific return for each discipline. By way of example, we will illustrate our methodology using three architectures. For each architecture, we will visualize science return by superimposing plots of the return from each discipline. For comparison, we first plot the science return from the Apollo program as a whole (figure 4a). Next, we conduct an intra-architectural comparison using the Exploration Emphasis architecture (LMEPO, 1990a; table 1) to illuminate the difference in science return for differing implementation choices within the same architecture (figure 4b and 4c.). Then, we determine science return for the Expanding Human Presence architecture (LMEPO, 1990b; table 2, figure 4d), comparing it with the Exploration Emphasis architecture for an inter-architectural comparison, and examining those mission scenarios likely to emphasize particular fields of science. The latter two architectures are based on those devised by the NASA JSC Exploration Programs Office, but are simplified for the purpose of discussion.

The Apollo Program

The Apollo program provides a handy example of a mission architecture that is well known. The scientific return from the Apollo program consisted of localized geoscience at six sites on the Moon, with astronomy addressed through the deployment of a single, suitcase ultraviolet telescope at one site. The representative plot in figure 4a accordingly consists of a small triangle for geosciences superimposed on a triangle for astronomy. Because laboratory science was absent in Apollo, no triangle is shown for it.

The Exploration Emphasis Architecture

The Exploration Emphasis architecture can be pursued at a modest or aggressive level (table 1). The

Apollo Program

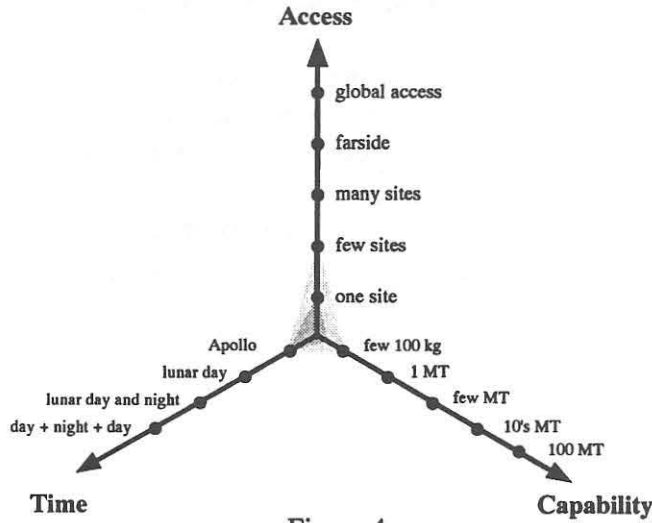


Figure 4a

Exploration Emphasis Modest Implementation

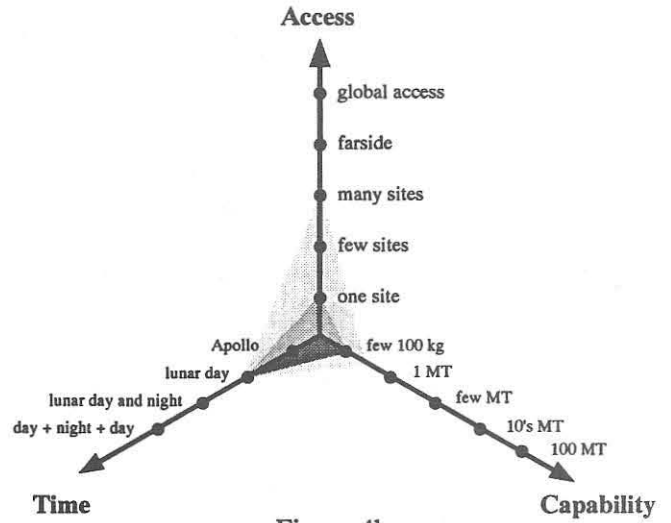


Figure 4b

Exploration Emphasis Aggressive Implementation

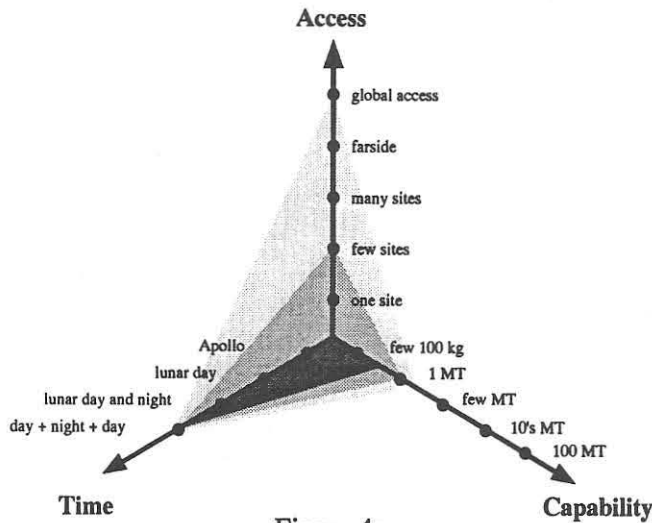


Figure 4c

Expanding Human Presence Aggressive Implementation

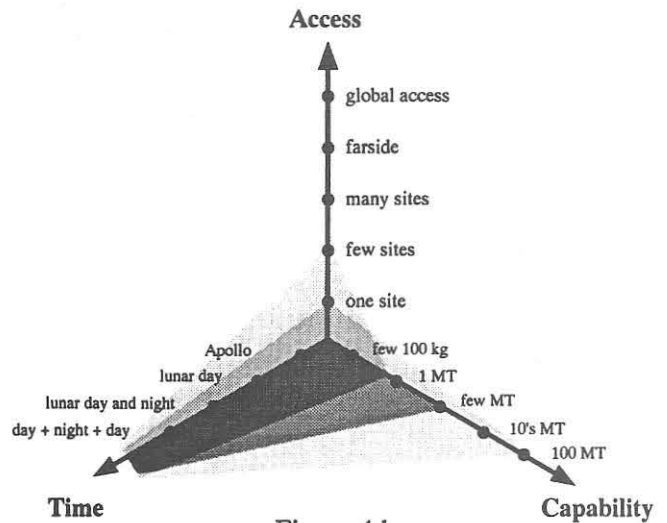


Figure 4d

Figure 4. Plots of the Apollo Program, the Exploration Emphasis, and Expanding Human Presence architectures on the three axes. The different architecture plots indicate both intra-architecture (figures 4b and 4c) and inter-architecture comparisons (figure 4c and 4d): (a) This is a plot of the total science return of the Apollo Program, for comparison purposes. Surface activities focused dominantly on geoscience, but a small, automated telescope was deployed at a single site (Apollo 16). No laboratory science was conducted on the Moon; (b) low-level or minimalist implementation of the Exploration Emphasis architecture; (c) high-level or aggressive implementation of the Exploration Emphasis architecture; and (d) the Expanding Human Presence architecture. Note the high return in astronomy and laboratory science for this architecture (cf. figure 4c).

implementation choice is likely to be driven by fiscal and operational constraints, not scientific considerations. However, our evaluation process permits us to see the relative scientific return, both by discipline and collectively, for different implementations of the same architecture (figure 4b and 4c). Beyond the obvious relation that more capability produces greater scientific return, we see that this architecture yields the greatest leverage for geoscience. Astronomy has a poor return in constrained implementations of this architecture (figure 4b), but becomes quite robust at more aggressive levels (figure 4c). Laboratory sciences fare relatively poorly in this particular architecture, whatever implementation is selected. This result is not surprising as the architectural theme stresses exploration, mobility, and access. The total, cumulative science return (combined area of surfaces plotted in figure 4b and 4c, respectively) is quite high, whichever degree of implementation is used.

The Exploration Emphasis architecture is very productive scientifically, with particular strengths in planetary geoscience. We see that total science return is greatly increased by selecting 45-day surface times (i.e., day-night-day on the time axis, figure 4c) over a single lunar day (14-days) surface time (figure 4b). On the other hand, increasing landed mass does *not* increase the total science return at the same rate (cf. time and capability axes in figures 4b and 4c). Increasing surface stay time provides greater increases in the total scientific return than does increasing landed payload mass. Finally, the Exploration Emphasis architecture, while robust for science in general and geoscience in particular, can be made even more productive by making specific implementation choices that give maximum leverage in the science return.

The Expanding Human Presence Architecture

In addition to aiding in selecting implementation options within a given architecture, this process of evaluation can help distinguish different architectures in terms of science return and discipline emphasis. The Expanding Human Presence architecture (table 2), emphasizes the rapid build-up of infrastructure and people at a single site on the Moon. Such a scenario produces a much different return for science (figure 4d) than does the Exploration Emphasis approach (figure 4c). Because the Expanding Human Presence scenario involves high levels of delivered mass, continuous crew time, and a large amount of

Table 1. Features of the Lunar Portion of the Exploration Emphasis Architecture

Modest Implementation

- 1 lunar mission per year - access to multiple sites on near and far sides of the Moon
- 2 week excursion, no pre-reconnaissance
- Crew of 3, live in lander, unpressurized rover
- Exploration tools, suitcase instruments deployed
- Minimal lab work on Moon

Aggressive Implementation

- 3 lunar missions per year - global access to multiple sites
- 6 week excursions, deployment of teleoperated rover for site pre-reconnaissance
- Crew of 6, live in lander, unpressurized rover
- Exploration tools, multiple suitcase instruments deployed
- Minimal lab work on Moon

Table 2. Features of the Lunar Portion of the Expanding Human Presence Architecture

- Select single outpost site on the Moon; 1-2 resupply missions per year
- Intensive investigation of near-field around outpost (minimal roving capability)
- Crew build-up from initial capability of 6 (and up to 30) for 2-3 year tour of duty
- Initial emphasis on habitat, base facilities. Continuously expanded laboratory space
- Large-scale construction on the Moon. Large telescope and array observatory facilities at variety of wavelengths
- Large amounts of mass landed on the Moon (on order of few 100 metric tons/year) to support robust infrastructure

leveraging infrastructure, both astronomy and laboratory sciences have a very high return. However, the parameter of access, important for geoscience return, is minimal in this architecture; thus, geoscience return is significantly lower than for the previous example (cf. figures 4c and 4d). A conclusion of the inter-architectural comparison is that while both architectures produce high scientific return, the Expanding Human Presence scenario offers significant advance to the observational and laboratory sciences, whereas the Exploration Emphasis scheme makes its major contribution to geoscience. The use of our methodology can thus illuminate differences between architectural themes, in addition to aiding in implementation choices.

Final Evaluation

Choices of architectural themes and SEI mission goals are policy decisions, made at the national, strategic level. These thematic decisions set boundaries within which engineers must make implementation decisions. Such architectural details are driven by cost, schedule, and performance constraints. A myriad of implementation choices are possible and many of these may be more or less equal within the overall constraints imposed by the scale and mission envelope of the program. It is at this level that our method is intended to be used.

We believe that science is an important part of the Space Exploration Initiative. Our goal is to maximize the scientific return of architectures by illuminating and distinguishing implementation choices for various disciplines. Examining the degree to which science objectives are met, using the parameters described in this discussion, can help planners design a mission that meets mission goals while at the same time providing for a rich and never before imagined harvest of scientific knowledge.

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